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Decay rates for doubly even $N = 84$ α emitters and the subshell closure at $Z = 64$†

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Up-to-date decay energies and half-lives for doubly even $N = 84$ α emitters (from ^{144}Nd to ^{154}Yb) were used to determine their reduced widths for α decay. It was found that, as had been predicted earlier by Bardeen-Cooper-Schrieffer calculations, the reduced widths reach a minimum at $Z = 64$ and not at $Z = 66$, as older data had indicated. As part of the study the α-decay energy of ^{154}Yb was redetermined to be 5.318±0.005 MeV.

[RADIOACTIVITY ^{154}Yb; redetermined E_α. ^{144}Nd, ^{146}Sm, ^{148}Gd, ^{150}Dy, ^{152}Er, ^{154}Yb; deduced α-decay reduced width.]

A proton subshell at 64 was first suggested[1] when a discontinuity in the progression of α-decay energies for $N = 84$ nuclides was noted at $Z = 64$. To obtain some theoretical understanding of this subshell closure Macfarlane, Rasmussen, and Rho[2] made calculations using a Gaussian residual force in a BCS treatment for the proton system of 82-neutron nuclei. By assuming a sufficient spacing between the $d_{5/2}$ and $h_{11/2}$ proton orbitals their calculations produced a discontinuity in theoretical binding energies at $Z = 64$. In addition, they calculated relative reduced α-decay transition probabilities for the $N = 84$ even nuclei. Once again these theoretical reduced widths indicated a significant dip at $Z = 64$. Maxima were predicted at about $Z = 60$ and $Z = 74$ with the reduced widths decreasing in magnitude as the 50- and 82-proton closed shells were approached. Contrastingly, reduced widths determined[2] from then available experimental data for ^{144}Nd, ^{146}Sm, ^{148}Gd, ^{150}Dy, ^{152}Er, and ^{154}Yb indicated a general constancy in value except for a dramatic reduction (by about a factor of 2) for ^{150}Dy, i.e., at $Z = 66$.

The ^{150}Dy reduced width was based on an α-decay branching ratio of 0.18 ± 0.02.[3] A recent measurement, utilizing a high resolution Ge(Li) x-ray detector, reported[4] a value of 0.32 ± 0.05. This higher value produced a ^{150}Dy reduced width very much in line with those for the other $N = 84$ even α emitters. The newer branching ratio has now been confirmed[5] with values of 0.31 ± 0.03, obtained once again from $K\alpha_1$ x-ray intensities, and 0.36 ± 0.03, obtained from the ^{150}Dy electron-capture decay scheme.

This large decrease in the ^{150}Dy partial α-decay half-life prompted us to examine the data currently available for these $N = 84$ nuclei. It was found that (with the exception of ^{150}Dy) no significantly different half-life measurements had been reported since the survey made in Ref. 2. However, the α-decay energies of ^{144}Nd, ^{148}Gd, ^{150}Dy, and ^{152}Er were now much more accurately determined. In particular, the α-particle energy for ^{148}Gd (long recognized as an ideal low-energy α calibration source) had recently been measured[6] to be 3182.787 ± 0.024 keV. These developments indicated that it would be worthwhile to obtain a new set of reduced widths to compare with the BCS calculations.

Further, we were in a position to obtain a new determination of the ^{154}Yb α-decay energy. Bowman, Hyde, and Eppley[7] have made available a list of accurate energies for about 40 α-emitting nuclides, many of them in the rare earth region. Most of these, including ^{150}Dy and ^{152}Er, now have quoted errors of ± 3 keV. We reexamined earlier spectral data[8] where ^{154}Yb had been observed in the midst of a large number of nuclides appearing on this list.[7] With the aid of these internal calibration standards we determined the E_α of ^{154}Yb to be 5.318 ± 0.005 MeV. The energy used in Ref. 2 was 5.33 ± 0.02 MeV.

As had been done in Ref. 2, the reduced widths were calculated using the α-decay formalism developed by Rasmussen.[9] In it an α-decay reduced width δ^2 is defined by the equation

$$\lambda = \delta^2 P/h,$$

where λ is the decay constant, h is Planck's constant, and P is the penetrability factor calculated for a barrier that contains a diffuse nuclear potential. This potential was derived by Igo[10] from the analysis of α-particle scattering data.

Table I summarizes the δ^2 values together with the decay energies and half-lives (Refs. 5–8, 11–19) used to determine them. In Fig. 1(a) we have plotted these reduced widths, while in Fig. 1(b) we

TABLE I. Reduced widths for $N=84$ α emitters.

Nuclide	E_α	$T_{1/2}(\alpha)$	δ^2 (MeV)
^{144}Nd	1848.8 ± 2.8 keV[a]	$(2.29\pm0.24)10^{15}$ yr[b]	$0.149\pm{}^{0.038}_{0.030}$
^{146}Sm	2.46 ± 0.02 MeV[c]	$(9.99\pm0.46)10^{7}$ yr[d]	$0.098\pm{}^{0.086}_{0.045}$
^{148}Gd[e]	3182.787 ± 0.024 keV[f]	92.9 ± 5.2 yr[g]	0.087 ± 0.005
^{150}Dy	4.232 ± 0.003 MeV[h]	$(1.30\pm0.10)10^{3}$ sec[i]	0.105 ± 0.012
^{152}Er	4.779 ± 0.003 MeV[h]	$11.2\pm{}^{3.6}_{0.9}$ sec[j]	$0.124\pm{}^{0.017}_{0.033}$
^{154}Yb	5.318 ± 0.005 MeV[k]	0.40 ± 0.04 sec[l]	$0.129\pm{}^{0.022}_{0.018}$

[a] Reference 11.

[b] Weighted average taken from Refs. 12 and 13.

[c] Reference 14.

[d] Weighted average taken from Refs. 14 and 15.

[e] In Ref. 16 the electron-capture branch of ^{148}Gd has been measured to be $<1.3\times10^{-4}$ *vis-à-vis* its α-decay branch.

[f] Reference 6.

[g] Weighted average taken from Refs. 15 and 17.

[h] Reference 7.

[i] Average taken from Ref. 5.

[j] Weighted average taken from Refs. 5 and 18.

[k] Determined from a reevaluation of α-decay data published in Ref. 8 using some of the energies listed in Ref. 7 as internal standards.

[l] Reference 19.

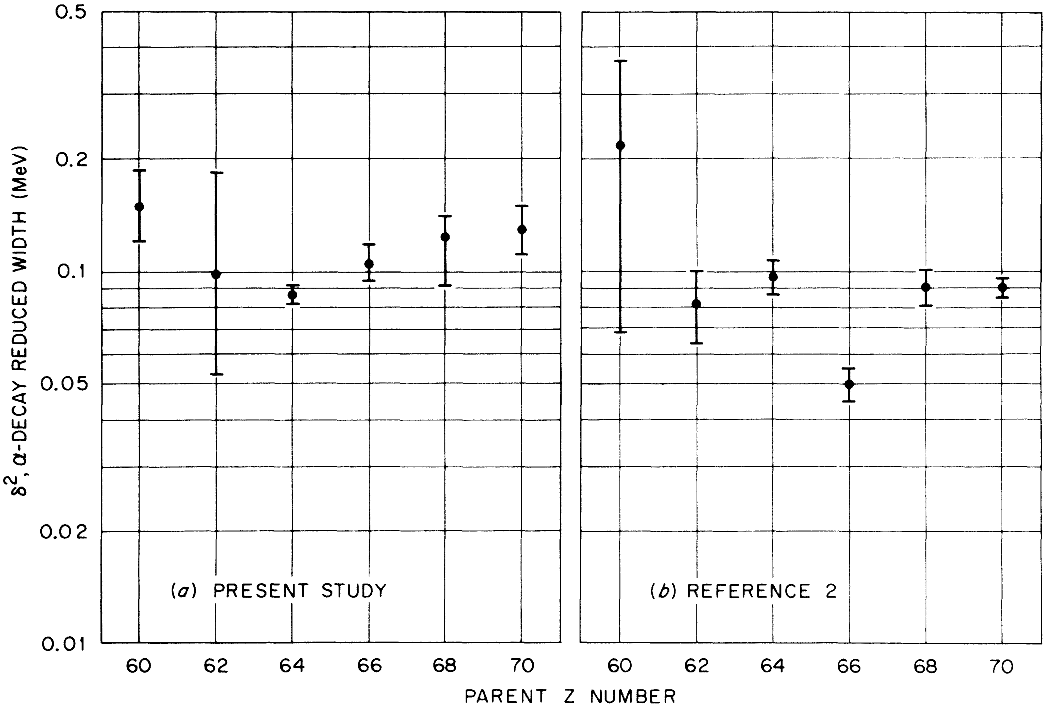

FIG. 1. Part (a) shows reduced widths (δ^2) for $N=84$ even α emitters that were calculated using up-to-date experimental information. These δ^2 values are also listed in Table I. Part (b) shows reduced widths for the same nuclei taken from Table I presented in Ref. 2.

show the δ^2 values listed in Table I of Ref. 2. The new determinations shown in Fig. 1(a), in contrast to those in Fig. 1(b), indicate that the dip occurs at $Z = 64$ as the BCS calculations predicted.[2] Also, in agreement with the calculations, the new reduced widths show an increase in value as $Z = 60$ and $Z = 72$ are approached. We should point out that the error limits given in Table I for the reduced widths are extreme ones, i.e., the upper (lower) limit in each instance was calculated by using the shortest (longest) half-life and the smallest (largest) decay energy. It is not clear how the error limits were determined in Ref. 2. However, if the same procedure had been followed then the errors should have been much greater than those shown in Fig. 1(b) (also listed in Table I of Ref. 2) because of the large uncertainties in the experimental decay energies available at that time.

The authors in Ref. 2 concluded on the basis of disagreement between the experimental data and the BCS predictions that the proton structure was not independent of neutron number. Their suggestion to explain the experimental dip at $Z = 66$ was that the α-decay daughter of ^{150}Dy, i.e., ^{146}Gd, has a low amount of proton pairing correlation but that the addition of two neutrons restores this correlation in ^{148}Gd. However, as mentioned above, Fig. 1(a) indicates agreement with the calculations. This could be made more apparent if the error limits in the ^{146}Sm δ^2 value were reduced. The errors are due mainly to the 20-keV uncertainty in the nuclide's α-decay energy. Thus, a new measurement which could decrease the ^{146}Sm E_α uncertainty to ~5 keV would be of great value.

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